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Penouille Spit, Evolution of a Complex Spit, Gaspé, Quebec, Canada

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ABSTRACT

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Penouille Spit is a complex spit located on the north shore of Gaspé Bay in Quebec, Canada. Rates of deposition and erosion were derived from old maps and aerial photographs of beach ridges and shorelines on Penouille dating from 1765 to 1981. In July 1989, 41 beach ridges were mapped along 7 traverses and sediment samples were collected along 15 beach profiles. A 6-stage model of spit evolution was derived from the beach ridge and shoreline data. At Stage 1, an arcuate spit formed on a submerged deltaic platform near the mouth of the l'Eau River. During Stages 2 and 3, the Spit expanded westward about 2.1 km and rotated 20° in a counterclockwise direction. At Stage 4, erosion started at the west end of the Spit while deposition continued midway along the south shore. During Stage 5, a pair of recurved spits formed at the southeast corner of Penouille while erosion continued along West Beach. Finally by Stage 6, the south shore had rotated 40° and the corner spits converged enclosing a salt marsh at the southwest tip of the Spit. Rates of erosion along West Beach (0.50 ± 0.08 m/yr) and beach ridge accretion (45.5 ± 7.3 yrs/ridge) were used to estimate the net sediment flux (1,000 ± 160 m^3/yr) and age of the Spit (2,110 ± 340 yBP). Wave refraction analysis provided evidence that Sandy Beach Spit on the south shore of Gaspé Bay blocked incoming storm waves and longshore currents, resulting in erosion along West Beach at 500 ± 80 yBP.

ADDITIONAL INDEX WORDS: *Age determination, erosion rate, longshore currents, regression analysis, sea level rise, sediment flux, wave refraction.*

INTRODUCTION

The diverse types of spits on the Gaspé Peninsula, Quebec, Canada, provide a fertile testing ground for the different hypotheses concerning the origin of spits. Four spits on Gaspé Bay, Penouille, Sandy Beach, Douglastown and Haldimand, are aligned in a general north-south direction, but have diverse origins (Figure 1). Penouille Spit is a complex spit near the head of Gaspé Bay on the south shore of the Forillon Peninsula. On the south shore of Gaspé Bay, Sandy Beach projects northward from Cape Haldimand on a submerged deltaic platform. South of Cape Haldimand, a pair of baymouth bars, Haldimand and Douglastown Spits, bracket the entrance to Saint Jean Estuary (Figure 1). At first glance, the alignment of four spits within 15 km distance suggests a common origin; coastal morphology, geology and subsurface stratigraphy of the spits indicate that they may have had distinct and diverse origins. In this paper, we focus on Penouille Spit and attempt to unravel its history and its relationship to the other spits on Gaspé Bay.

Sand spits are free standing forms attached to the coast at one point but showing a wide variety of different morphologies (ZENKOVITCH, 1967; KING, 1979; PETHICH, 1984 and CARTER, 1988). The locations and shapes of spits are controlled by several different geologic factors including longshore drift (JOHNSON, 1925), tidal and fluvial currents (FISHER, 1955), glacial and fluvial sediment supply (GUILCHER and KING, 1961), wave refraction and angle of wave approach (MAY and TANNER, 1973), and sea level rise (REDFIELD and RUBIN, 1962 and ZENKOVITCH, 1967).

Penouille Spit and Sandy Beach played important roles in the early French and English exploration of Quebec, Canada. In July, 1534, Jacque Cartier sailed into Gaspé Bay through, "a narrow passage where the great bars of Sandy Beach and The Peninsula (Penouille Spit) nearly strangle the waterway" (CLARKE, 1913, p. 113). On July

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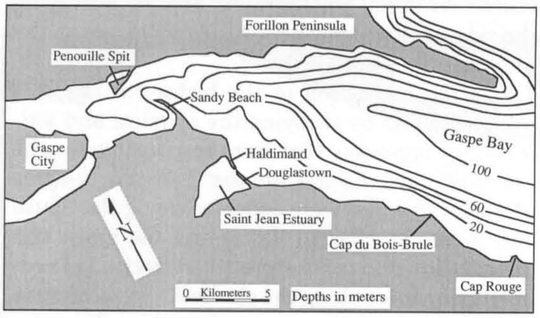

Figure 1. Map of sand spits and estuaries on Gaspé Bay at the eastern tip of the Gaspé Peninsula, Quebec, Canada. North arrows in all the Figures indicate true North.

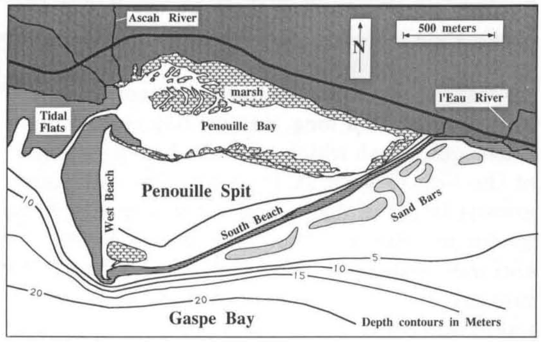

Figure 2. Geomorphic features of Penouille Spit on the north shore of Gaspé Bay, Quebec, Canada.

25, 1534, Cartier landed on Sandy Beach, erected a cross before an assembled group of Native Americans, and claimed possession of the country that became "New France" in the name of the King of France. Two hundred and twenty four years later in August 1758, General Wolfe entered Gaspé Bay with seven British ships and three regiments of soldiers and landed at the French fishing village on Penouille. Wolfe took over the French custom house for his command post; a month later, September 5, 1758, the French surrendered to the English (CLARKE, 1913).

In the mid 1800's, a whaling station for the Gulf of Saint Lawrence was established on Penouille Spit. In the early 1900s, whaling was abandoned and the Penouille became a summer resort area for Gaspé. In 1972, Penouille was incorporated into the Forillon National Park and the Spit began to return to its natural state.

LOCATION, GEOLOGIC SETTING AND GEOMORPHOLOGY

The Forillon Peninsula extends along the north shore of Gaspé Bay with Cape Haldimand, Cap du Bois-Brûlé and Cap Rouge marking its southern boundary (Figure 1). Gaspé Bay is formed within a V-shaped notch at the eastern tip of the Gaspé Peninsula where it projects into the Gulf of Saint Lawrence. The Bay is confined within the eroded top of an easterly plunging syncline that formed during the Late Paleozoic Acadian Orogeny (ALLARD and TREMBLAY, 1979). Red and green cross-bedded sandstones of the Lower to Middle Devonian Battery Point Formation crop out along the north and south shores of the bay (MCGERRIGLE, 1985). The sandstones dip steeply to the south along the north shore of the bay adjacent to Penouille Spit. Shales and siltstones along the coast are eroded back exposing coarser layers of sandstones and conglomerates in bas relief. Sandstone cliffs are exposed along the coast to the east and west of the Spit, but gently sloping grass covered hills extend to the waters edge behind the marsh to the north of the Spit.

Penouille Spit dangles into Gaspé Bay from the south shore of the Forillon Peninsula like the pelvic fin on an Atlantic salmon (Figure 2). The main body of the Spit extends about 2 km in a southwest direction and is 860 m wide along its western shore. The Spit sits upon a shallow platform which extends southward along the north shore of the bay. At its northeast corner, the triangular spit is attached to the mainland by a narrow isthmus of sand less than 40 m wide and over 500 m long (Figure 2).

South Beach extends 2.6 km in a southwest direction from sandstone cliffs to a small recurved spit at the tip of the peninsula (Figure 2). South Beach is flanked by sand bars on a gently sloping platform of sand. The tops of the bars emerge above sea level at low tide and are submerged about 1.5 m at high spring tide. At the east end of the beach, the bars extend about 250 m offshore. To the southwest, the bars approach the shore and merge with the beach about 500 m from the western tip of the Spit.

Along the west shore of the Spit, a narrow beach is bordered by a gently sloping tidal flat (Figure 2). The tidal flat is distinguished by the absence of sand bars which are so prominent along South Beach. At the back of the beach, a 1 to 2 m high sand scarp marks where westward trending beach ridges and dunes have been truncated by recent erosion. Small recurved spits at the north and south ends of West Beach provide further evidence for erosion.

A tidal channel at the northwest corner of the Spit opens into a long, narrow bay containing a broad salt marsh which extends the entire length of the Spit (Figure 2). High and low salt marsh grasses line the north and south shores of the marsh, and ebb and flood tidal deltas enclose the entrance to the bay. The Ascah River, which flows into the northwest corner of the bay, supplies sediment and nutrients to the marsh.

Penouille Spit rests on a broad fan-shaped platform that extends about a kilometer southward into Gaspé Bay between the mouths of the Ascah River and the l'Eau River (Figure 2). The rivers may have contributed sediment to a deltaic platform during the Holocene rise in sea level (SCOTT and MEDIOLI, 1980). As water level in the bay approached its present level, sediments discharged from the l'Eau River provided a source of sand for Penouille Spit.

Additional sediment for the Spit was provided by long shore currents sweeping along the north and south shores of the bay. Large waves and swells from storms in the Gulf of Saint Lawrence were funneled into Gaspé Bay where they eroded the sandstone cliffs along its margin (Figure 1). The sediments derived from the rivers and cliffs were transported westward by swash and backwash of refracted waves and longshore currents along the south shore of the Forillon Peninsula. Where the rate of sediment supplied by long shore currents exceeded the rate of beach erosion, sand was deposited as spits which built out into the Bay (MAY and TANNER, 1973). Strong ebb and flood tidal currents flowing around the southwestern tip of Penouille also influenced the shape and evolution of the Spit.

METHODS

The evolution of Penouille Spit has been documented by a combination of several different techniques. The recent history of the Spit has been determined by plotting the positions of shorelines on a series of maps dating from 1765 to 1948 and from aerial photographs taken from 1948 through 1981. The Spit was resurveyed in 1989 with 7 north-south traverses across the Spit and 16 beach profiles normal to the south and west shore. The evolution of the Spit was interpreted by plotting beach ridges where they are visible on aerial photographs and by surveying the ridges where they were hidden by trees on the photos.

The reconstruction of the history of the Spit was also aided by studying the physical and sedimentary processes that were responsible for the accumulation of sand on the Spit. Forty-three sediment samples were collected along the South and West Beaches to determine the grain size distribution and to interpret the direction of sediment transport along the shore. Analysis of wave refraction diagrams presented in this study also provided estimates of the direction and magnitude of longshore currents under different storm conditions along the Spit.

Maps and Aerial Photographs

The erosion rates on Penouille Spit were estimated from shoreline traces on the old maps and aerial photos (Figure 3). Many of the old maps, which are stored in the archives of the Jacque Cartier Museum in Gaspé City, Quebec, were reproduced in a book on the topography of Penouille (MIMEAULT, 1980). Although the surveying methods and accuracy of the early maps vary considerably from 1765 to 1948, the maps provide a reasonable estimate of the changes in the size and shape of the Spit over the past 224 years.

After General Wolfe occupied the Spit in 1758, he anglicized the name from "Penouille" to "Peninsula". The English name, Peninsula, appeared on subsequent maps of Gaspé Bay until the 1960s when the Quebec Provincial government renamed the Spit "Penouille". The earliest known detailed map of Penouille (Figure 3A) dates from 1765 as part of *A Plan Of the Bay and Harbor of Gaspey* by John Collins (MIMEAULT, 1980). The large rectangular plots which Collins surveyed for the colonization of the lands around Gaspé Bay can still be traced as plowed fields on recent aerial photographs. The overall shape of the peninsula on the 1765 map resembles the 1948 map of Penouille (Figures 3A and 3F). However, in 1765, the northwest coast of the Spit projected farther to the west than in 1948, and the isthmus of sand, where it joins the mainland, was broader and extended farther to the east.

The Spit was remapped in 1781 by the crew of the British vessel Neptune, and it had the same general shape but with a broad embayment along the western shore and two protuberances on the

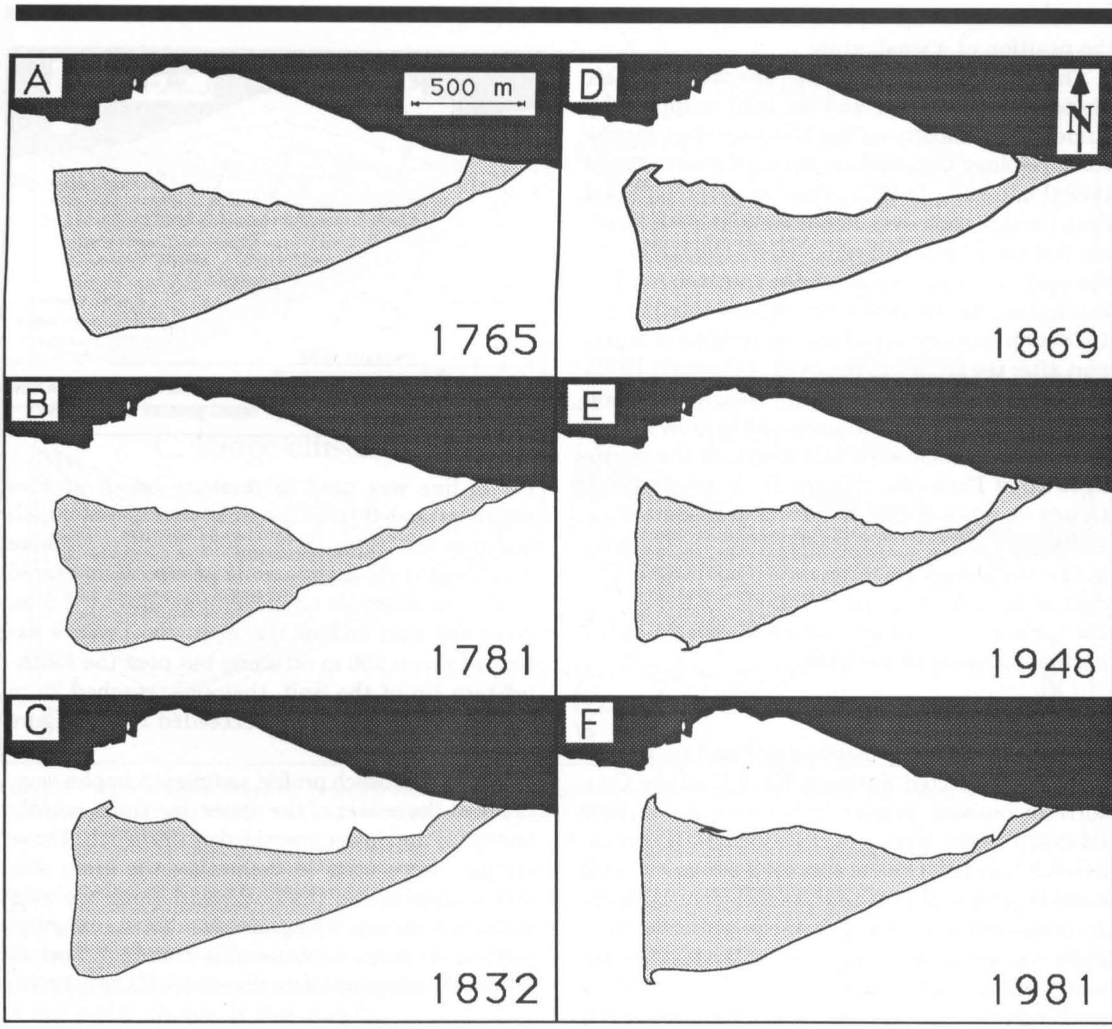

Figure 3. Six maps of shoreline traces showing the evolution of Penouille Spit from 1765 to 1981.

south shore (Figure 3B). Even with the embayments, the average extent of the western shore in 1781 spit is similar to that of 1765.

The 1832 map compiled by H. W. Bayfield (Figure 3C) has small recurved spits on the north and south ends of West Beach (MIMEAULT, 1980). The west end of the Spit was eroded considerably between 1781 and 1832, and the protuberances on South Beach have been smoothed out. The northern border along the edge of the marsh also changed considerably between 1765 and 1832.

The 1869 map by H. W. Redfield (Figure 3D) shows that the small spit at the northwest corner of the 1832 map had expanded, and the spit at the south end of West Beach had eroded (MIMEAULT, 1960). The beach along the south shore of the Spit was straightened out by 1832, but the north shore along the marsh is similar to the marsh mapped in 1832.

The 1948 map of Penouille (Figure 3E) was based on the 1:12,000 Hydrographic Chart, *Havre de Gaspé* (Chart 4116) surveyed by the CANADIAN HYDROGRAPHIC SERVICE (1983). The shoreline of Penouille Spit was based on 1948 aerial photos with additional bathymetric data in Gaspé Bay based on hydrographic surveys 1980 and 1981. The south shore of the 1948 map shows a small westward pointing spit at the bend in the shoreline about 300 m from the southwest corner of the main spit (Figure 3E). There is also a sharp bend about midway along the south shore which marks the position of a small groin.

The 1981 map of the Spit was based on air photos taken in 1981 and on field mapping by students and faculty on the Gaspé project for the Keck Geology Consortium during the summer of 1989 (Figure 3F). In 1972, The Canadian National Park Service took over Penouille as part of Forillon National Park and removed all the houses on the Spit and the groin along the south shore. The bend along South Beach which was noted in the 1948 map was smoothed out by longshore transport after the groin was removed in the early 1970s. The small spit along the South Beach which was present in the 1948 map continued to grow toward the west and enclosed a salt marsh at the southwest tip of Penouille (Figure 2). As erosion continued on West Beach, sand was transported toward both ends of the beach enlarging the spits at the north and south corners (Figure 3F). The narrowing isthmus of sand connecting the Spit to the mainland indicates continued erosion at the northeast corner of the Spit.

Field Work

Penouille Spit was mapped and sediment samples were collected during a Keck Geology Consortium research project in the summer of 1989 (Haney, 1990). Seven north-south transects labeled A through G were surveyed across the Spit roughly perpendicular to the south shore (Figure 4). A baseline was established along the National Park Service road to provide a reference line for points along each of the profiles. The transects were oriented using a Brunton compass along magnetic north which is 23° west of true north in Gaspé. Distances along each transect were measured with a steel tape at 45.7 m (150 foot) intervals. North of the road, distances to beach ridges, salt ponds, and the edge of the salt marsh were recorded. Since the positions of the ponds have not changed since the 1981 air photo and map of the Spit, their intersections along each transect provided additional checks for distances and orientations measured in the field. South of the road, beach ridges, driftwood lines, the seaward edge of the beach grass and low tide shoreline were also recorded.

Beach profiles and sediment samples were taken at 8 stations spaced at 100 m intervals along the south shore and at 8 stations spaced at 30 m intervals along the west shore (Figure 4). The stake and horizon method with two 1.5 m stakes and a

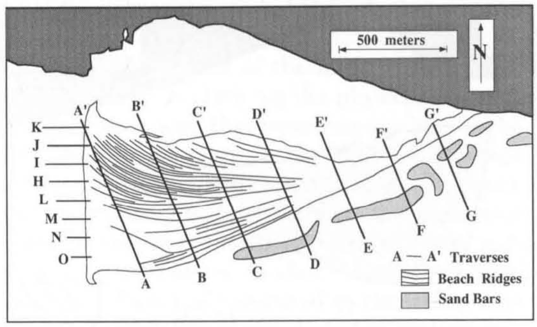

Figure 4. Map of beach ridges and sand bars on Penouille Spit with traverses A through G and beach profiles H through O.

6.1 m line was used to measure beach profiles which extended from the dunes across the beach and into the water (Fox, 1983). In the nearshore area, depths along the profile lines were measured at 30.5 m intervals offshore to a depth of 1.5 m. Near the east end of the Spit, the profiles extended about 250 m offshore; but near the southwestern tip of the Spit, they only reached 25 m offshore before the depth exceeded 1.5 m (Figure 4).

Along each beach profile, sediment samples were taken at the center of the upper one-third, middle one-third and lower one-third of the beach. These samples were used to determine the grain size distribution across the beach and along the west and south shores. The grain size distribution was plotted on maps to determine the directions of sediment transport along the shore (Haney, 1990).

Beach Ridge Clusters

A 1 m by 1 m enlargement of the 1979 aerial photograph of the Spit was used to trace the curved beach ridges along the northern half of the Spit (Figure 5A). The beach ridges mark the positions of relict primary dunes which were formed adjacent to an active beach. Sediment deposited on the beach by waves and longshore transport was blown shoreward by wind forming beach ridges parallel to the shore. Therefore, the beach ridges can be used to trace the position of the shoreline and evolution of the Spit through time (Kaye, 1961; El-Ashry, 1966 and Curray, *et al.*, 1967).

On the northern half of the Spit, beach ridges are clearly evident from the vegetation patterns and shadows on the enlarged aerial photograph. However, along the southern half of the Spit, beach ridges are partially covered by a dense growth of

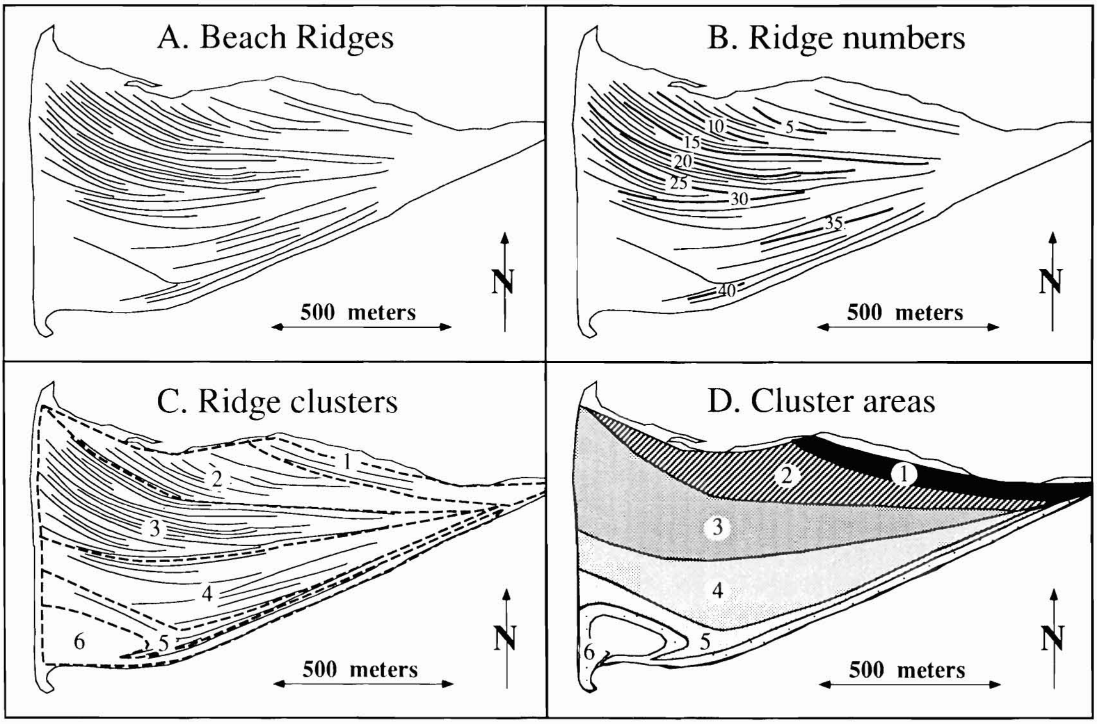

Figure 5. Maps of beach ridges on Penouille Spit including; (A) plot of observed ridges, (B) numbering system of the 41 ridges, (C) 6 clusters of ridges, and (D) map patterns used to distinguish the 6 clusters.

cedar woods and are difficult to trace on aerial photographs. By correlating location and orientation of the beach ridges encountered along traverses through the woods with the traces of ridges on the aerial photos, it was possible to map the location of 41 beach ridges on the Spit (Figures 5A and 5B).

From the shape and orientation of the 41 beach ridges, they were grouped into 6 distinct clusters (Figure 5C and 5D). With 41 ridges, an immense number of cluster arrangements was possible. The beach ridges with similar orientations and shapes were grouped into clusters. Several different combinations of ridge clusters were tried before the final 6 clusters were selected. The natural sequence of ridges in the 6 clusters can be used to represent changes in depositional patterns on the spit.

RESULTS

Spit Evolution Model

A 6-stage model for the evolution of Penouille Spit was derived from the 6 clusters of beach ridges in Figure 5D. The ridge clusters represent erosional remnants of earlier spits that extended farther west than the present Penouille Spit. As new sediment was added to expand an existing spit, erosion also modified the shape of the previous spit. Therefore, in order to work out the sediment budget for the spit through time, it was necessary to reconstruct the extent and shape of the spit at each stage in its evolution.

The pair of ridges which run roughly parallel to the north shore were joined to form cluster 1 (Figures 5C and D). The initial scimitar-shaped spit was attached to the mainland at the l'Eau River and extended eastward about 2.1 km (Figure 6A). In the spit reconstruction, the spit thinned from 170 m at the east end to 70 m at its western tip.

A small segment of the 1989 spit is included with the initial spit in Stage 1 to show the spatial relationship between the base of the 1989 spit and the projected point of attachment of the initial spit (Figure 6A). If the base of the 1989 spit was attached to the ridge area in cluster 1 to form the initial spit, there would be a abrupt bend of about 40° where the spit in Stage 1 was attached to the 1989 segment. Because there is no reasonable geologic explanation for a sharp 40° bend in the initial spit, it is assumed that the initial spit continued eastward in a gentle curve and was connected to the mainland just east of the l'Eau River. Therefore, the location of the original spit may have been influenced by sediment that accumulated at the mouth of the l'Eau River and was distributed along the coast by westward flowing longshore currents (Figure 6A).

At Stage 2, the general arcuate shape of the spit was maintained as new beach ridges were accreted along the southwest margin of the spit. Ridges 3 through 12 from cluster 2 were added along the south and west edges of the initial spit (Figure 5C and 6B). During Stage 2, the northwestern end of each beach ridge terminated near the present south shore of the salt marsh. Sediment eroded at the northeast corner of the spit was deposited farther west along the spit or carried across the spit by overwash and deposited along the edge of the salt marsh resulting in a westward migration of the spit (Figure 6B). By the end of Stage 2, the spit was about 2.2 km long with a maximum width of 360 m.

During Stage 3, a large bulbous body of sand was added to the west end of the spit (Figure 6C). The third cluster of ridges numbered 13 through 30 forms a triangular wedge of sediment which is presently truncated along West Beach (Figure 6C). With ample evidence of active erosion along West Beach, it is assumed that the curved ridges in cluster 3 originally extended about 250 m west of the present (1989) shoreline (Figure 6C). The extent of westward expansion of the spit is based on the present width of the tidal flats adjacent to West Beach (Figure 2). During Stage 3, erosion continued at the northeast corner of the spit with overwash deposition in the marsh along the north side of the spit. The overall length of the spit increased from 2.2 to 2.4 km and the maximum width increased from 360 to 600 m. As the spit expanded to the southwest, the south shore rotated about 20° in a counterclockwise direction (Figure 6C).

During Stage 4, the center of deposition shifted to the east forming a bulge along the south shore (Figure 7A). Along the west shore, the tip of the bulbous spit deposited during Stage 3 was eroded forming a broad curved beach during Stage 4. Most of the sediment eroded from the west shore

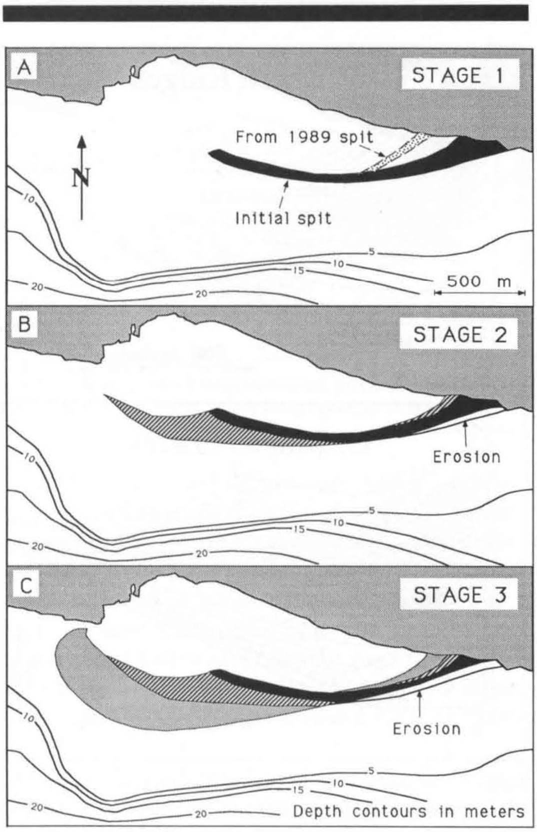

Figure 6. Model of the first three stages of growth and evolution of Penouille Spit. (A) Stage 1, initial scimitar-shaped spit with segment of 1989 spit for comparison, (B) Stage 2, spit growth to west with overwash deposition and erosion at east end, and (C) Stage 3, spit expansion to the west with overwash and erosion at the east end.

was deposited on the south shore in ridges numbered 31 to 37 (Figure 7A). With deposition concentrated along the middle of the south shore, the broadest part of the spit shifted to the east. Erosion continued at the northeast corner adjacent to the cliffs with deposition by overwash along the inner edge of the marsh (Figure 7A). During Stage 4, the overall length of the spit decreased by 200 m, the maximum width increased by 300 m to 915 m and the south shore rotated another 11° in a counterclockwise direction.

During the fifth stage of spit development, a small westward projecting spit started to develop at the bulge along the south shore (Figure 7B). Two small ridges, numbers 39 and 40, mark the initial position of the westward pointing spit. The westward longshore transport along South Beach

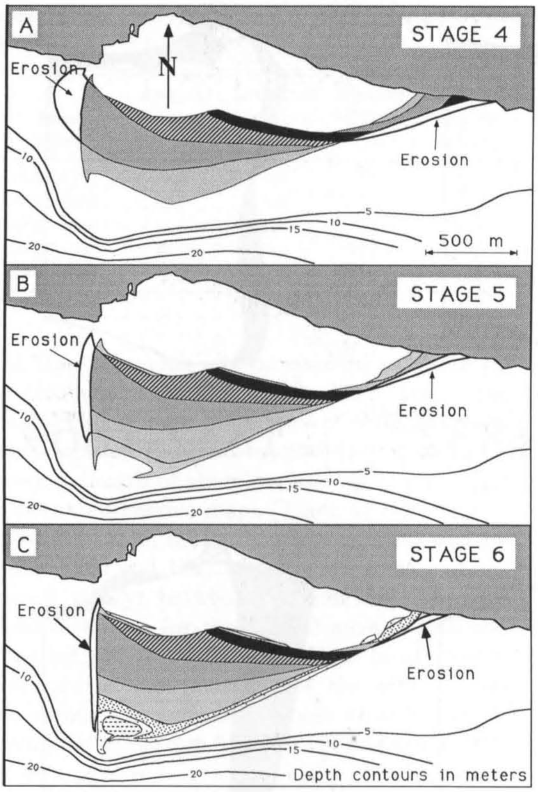

Figure 7. Model of the last three stages of growth and evolution of Penouille Spit. (A) Stage 4, deposition midway along the south shore with erosion along west beach and northeast corner, (B) Stage 5, converging spits at southwest corner with erosion along west beach and east end, and (C) Stage 6, spits merge at southwest corner forming a marsh with continued erosion on west beach and east end.

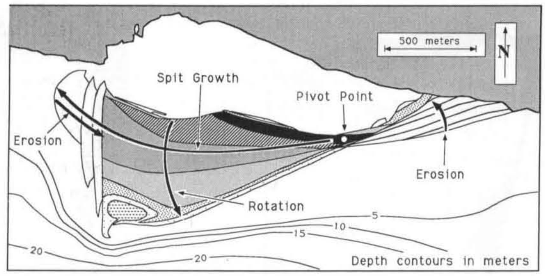

Figure 8. Composite map of 6 stage model showing expansion on the west end and counterclockwise rotation about a pivot point for Stages 1 to 3. During Stages 4 to 6, there was erosion along the west beach and deposition midway along the south beach with continued rotation about the pivot point. During Stages 5 and 6, spits developed at the southwest corner, then merged and enclosed a salt marsh.

provided sand for the spit. Wave erosion and longshore transport along West Beach also supplied sediment for a pair of small recurved spits at the north and south ends of West Beach. With the addition of the corner spits, the overall length of Penouille increased by 30 m, but the maximum width along the western shore increased by 160 m.

At the end of Stage 6, Penouille reached its present configuration. A pair of small spits at the southwest corner of Penouille converged and enclosed a salt marsh (Figure 7C). The spit at the south end of West Beach grew faster than the westward pointing spit on South Beach and formed the dominant recurved spit. Deposition along South Beach was evident from the single beach ridge, number 41, which was preserved behind the present foredune. Two lines of saw-cut logs roughly parallel to South Beach, mark the continued southward expansion of the shoreline. Saw-cut logs are also present along the north boundary of the marsh at the southwest tip of Penouille indicating recent growth of corner spits and enclosure of the marsh. Erosion continues along West Beach and at the eastern end of South Beach. During Stage 6, the length of the spit measured along the south shore decreased by about 150 m while the maximum width along West Beach increased by about 135 m.

Summary of Spit Evolution

The growth and evolution of Penouille Spit is summarized on a composite map that shows the six stages of deposition and erosion along with the rotation of the south shore (Figure 8). A pivot point marking the rotation of the spit has been plotted about a third of the way from the eastern end of the spit. Portions of the initial Stages 1, 2 and 3 are preserved west of the pivot point, but are eroded to its east. At Stage 1, the initial arcuate spit was attached to the south coast of the Forillon Peninsula. During Stages 2 and 3, the spit grew to the west as indicated by the broad arrow marked "Spit Growth" (Figure 8). To the east of the pivot point, the spit was eroded adjacent to the coast (Figure 8). During Stages 4, 5, and 6, the western end of the spit was eroded about 250 m. As beach ridges were accreted along the south shore, the spit rotated about 40° in a counterclockwise direction as indicated by the arrow marked "Rotation" (Figure 8). While the spit

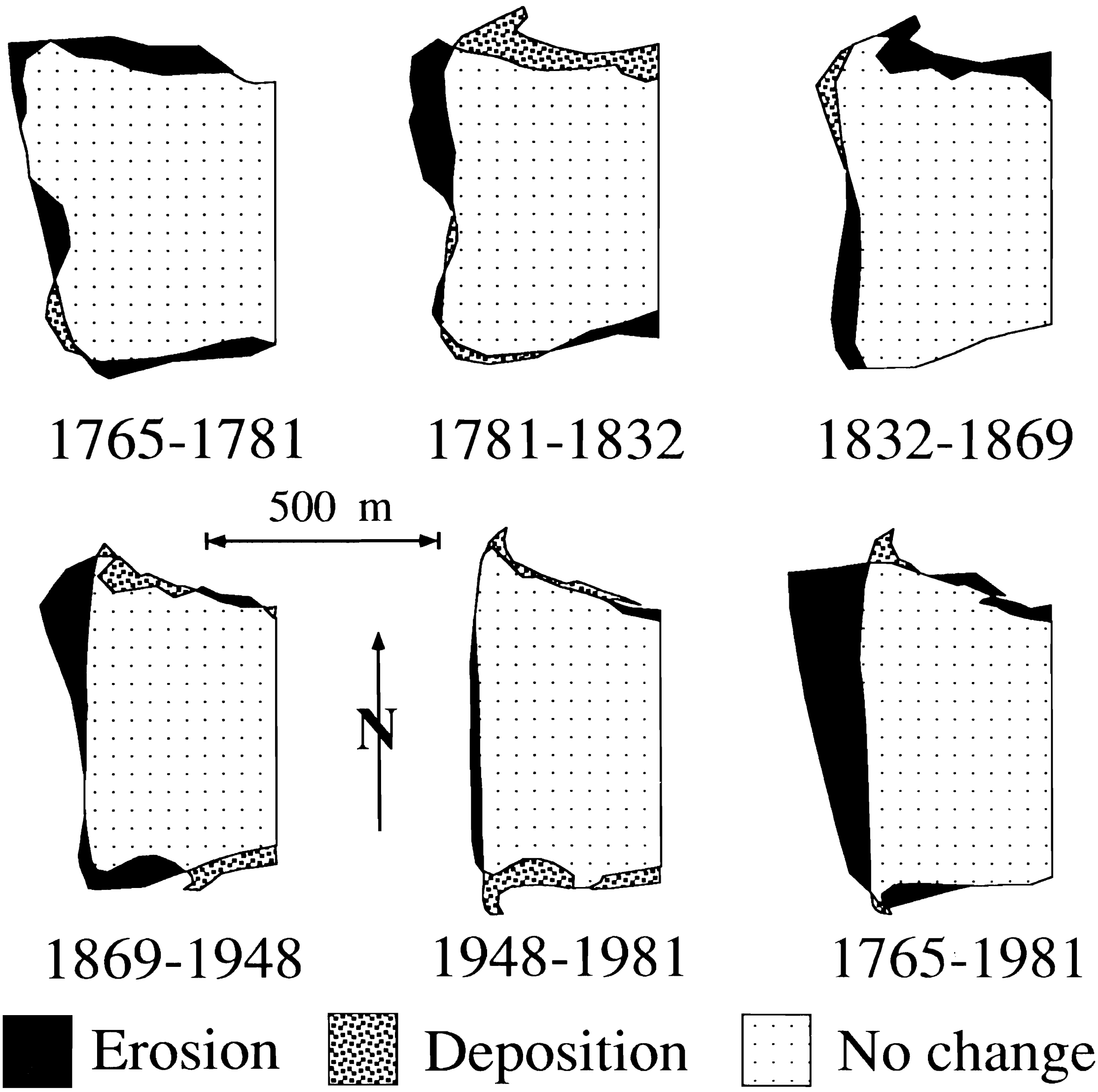

Figure 9. Maps of the western quarter of Penouille Spit showing areas of erosion, deposition and no change from 1765 to 1981.

rotated, erosion continued along the south shore to the east of the pivot point. During Stage 5, erosion continued along West Beach and a pair of spits formed at the southwest corner of the main spit. Finally, at Stage 6, the corner spits merged and enclosed a lagoon which was eventually closed off to form a salt marsh.

Erosion Rates

The average annual rate of erosion along West Beach can be used to estimate the ages of the 6 stages in the Spit evolution model and the age of origin of the Spit. The average rate of erosion along the West Beach was computed from the sequence of maps and aerial photos from 1765 to 1981 (Figures 3 and 9). The total area eroded along West Beach between 1765 and 1981 was 78.6 $\times$ 10^3 m^2. Assuming an average shoreline length of 730 m, the area of erosion per meter of shoreline is 108 m^2. Therefore, the average linear rate of erosion over the past 216 years is 0.50 m^2/ year.

The variation in rates of erosion during differ-

Table 1. *Average annual rates of erosion along the west beach at Penouille Spit based on the sequence of maps from 1765 to 1981 (Figures 4 and 11). The average rate of erosion from 1765 to 1981 was 0.50 ± 0.08 m/yr.*

Map Dates	Area of Erosion (10^3 m^2)	Length of Shoreline (m)	Number of Years (yr)	Rate of Erosion (m/yr)
1765–1781	9.3	730	16	0.81
1781–1832	22.3	710	51	0.62
1832–1869	11.0	710	37	0.42
1869–1948	26.1	710	79	0.45
1948–1981	9.9	770	33	0.39

Table 2. *Numbers of ridges and cumulative areas of deposition and erosion for each stage in the spit evolution model.*

			Cumulative		
Spit Stages	Ridge Numbers	Number of Ridges	Gross Deposition (10^3 m^2)	Gross Erosion (10^3 m^2)	Net Deposition (10^3 m^2)
1	1–2	2	111	0	111
2	3–12	10	225	13	212
3	13–30	18	503	44	459
4	31–37	7	676	118	558
5	38–40	3	752	165	587
6	41	1	825	211	614

ent time segments can be used to estimate the precision of the erosion rate for West Beach (Figure 9). The average annual rate of erosion for each time segment can be computed from the area of erosion, length of shoreline and number of years between successive maps (Table 1). The highest rate of erosion, 0.81 m/yr, was encountered between 1765 and 1781 with the lowest rate of erosion, 0.39 m/yr, between 1948 and 1981. The standard deviation for the annual erosion rate over the past 216 years (0.08 m/yr) can be used as an estimate of the precision of the erosion rate. Therefore, the estimated linear erosion rate for Penouille Spit from 1765 to 1981 would be 0.50 ± .08 m/yr.

Deposition and Erosion in Spit Evolution Model

The number of ridges included in each stage, and the cumulative areas of erosion and deposition at the end of each stage can be used to calculate the rates of erosion and deposition and the ages for Stages 1 through 6 in the spit evolution model (Table 2). The areas of erosion and deposition for each stage were computed from the digitized maps plotted in Figures 6 and 7. The numbers for the last ridge in each stage versus the areas for cumulative gross erosion and deposition are plotted in Figure 10. As the spit expanded to the south and west in Stages 1 through 3, the area of gross deposition increased from 111 to 503 × 10^3m^2 (Table 1). During the same time interval, the area of gross erosion at the northeast corner of the spit (Figure 8) increased from 0 to 44 × 10^3m^2 (Table 1).

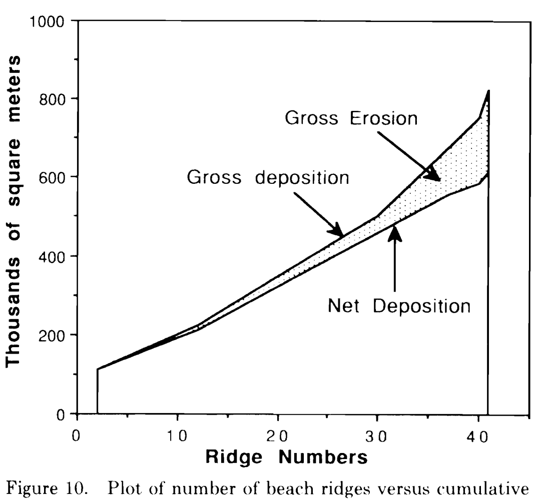

Figure 10. Plot of number of beach ridges versus cumulative areas of deposition and erosion for the 6-stage model.

At the end of Stage 3, erosion was initiated along the west coast of the spit (Figure 10). Although the rates of gross erosion and gross deposition represented by the slopes of the curves increased in Stages 4 through 6, the rate of net deposition (gross deposition minus gross erosion) remained relatively constant from Stage 1 through Stage 6 (Figure 10). The increase in gross erosion along West Beach during Stages 4 to 6 was largely balanced by increased deposition along South Beach (Figure 7A). From Stage 1 to Stage 6, a steady supply of new sediment from the east was being added to the south shore of the spit. Therefore, the rate of net deposition remained almost constant throughout the entire growth of the spit.

Age of Penouille Spit

Although it was not possible to obtain materials containing radioactive carbon (C^{14}) to determine the age of the Spit, the age was estimated from the average rate of erosion along West Beach and the number of ridges in each stage. First, it must be assumed that the average erosion rate along

Table 3. *The areas and estimated ages in years before present for the origin of the spit and at the beginning of each stage in the spit evolution model.*

Spit Stage	Ridge Number	Number of Ridges	Total Area (10^3 m^2)	Age (ybp)
Origin	0	0	0	2,110 ± 340
1	1–2	2	111	1,870 ± 290
2	3–12	10	212	1,770 ± 280
3	13–30	18	459	1,310 ± 210
4	31–37	7	558	500 ± 80
5	38–40	3	587	180 ± 30
6	41	1	614	45 ± 7

West Beach (0.50 ± 0.08 m/yr) which was determined from the maps and aerial photos over the past 216 years (Table 1) is representative of the average erosion rate during Stages 4 through 6. In the spit evolution model, the distance eroded normal to West Beach from the beginning of Stage 4 to the end of Stage 6 is 250 m (Figure 9). With an erosion rate of 0.50 ± 0.08 m/yr, the time interval between the beginning of Stage 4 and the end of Stage 6 would be approximately 500 ± 80 years.

During stages 4, 5 and 6, 11 beach ridges were deposited along the south shore of Penouille. Based on the almost straight line curve for number of ridges versus area of net deposition (Figure 10), it can be assumed that the ridges were accreted to the spit at an almost constant rate. Therefore, the average time interval for the accretion of each beach ridge would be 45.5 ± 7.3 years (500 ± 80 yrs/11 ridges = 45.7 ± 7.3 yrs/ridge). Knowing the average time interval for the accretion of each ridge and the number of ridges in each stage, it is possible to estimate the age at the beginning of each stage in years before present (yBP). For example, Stage 6 contains 1 ridge. Therefore, the estimated age at the beginning of Stage 6 would be 45.5 ± 7.3 yBP. Stage 5 contained 3 ridges. With the addition of the single ridge for Stage 6, the total number of ridges to the beginning of Stage 5 would be 4 giving an estimated age of 182 ± 29.2 yBP. The rounded off ages at the beginning of each stage are listed in Table 3.

Knowing the age at the beginning of each stage and assuming that the rate of net deposition remains constant, it is possible to estimate the age of the Spit from a regression line (Y = 606 + 0.287 X) for net deposition (Figure 11). By setting Y equal to zero and solving the regression equation for X, the regression line crosses the X axis at 2110 yBP. Therefore, the estimated age for the origin of the Spit would be 2110 ± 340 yBP (Table 3).

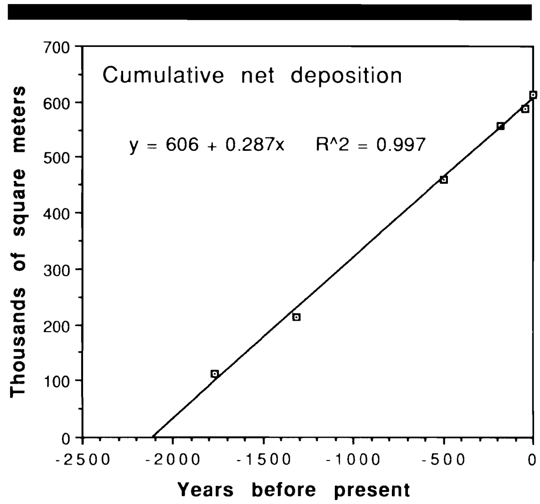

Figure 11. Plot of linear regression line for time versus cumulative areas of net deposition (gross deposition minus gross erosion) for Stages 1 through 6 on Penouille Spit.

Sediment Flux

Sediment fluxes can be computed from the rates of areal erosion and deposition and the average thickness of the Spit. If it is assumed that the sediment platform upon which the Spit rests is about 1.5 m below mean sea level, and the mean elevation of the surface of the Spit is about 2.0 m above mean sea level, then the average thickness of the Spit would be about 3.5 m. The slope of the regression line for net deposition is 0.287 giving a net depositional rate of 287 ± 46 m^2/yr (Figure 11). Therefore, net sediment flux for Stages 1 through 6 would be approximately 1000 ± 160 m^3/yr (3.5 × 287 × 287 = 1004.5).

The close fit of the regression line to the data points reflected in the high R^2 value (0.997) would indicate that the sediment flux remained steady through time (Figure 11). The steady sediment flux can be accounted for by the constant erosion rate of sandstone cliffs along the south shore of the Forillon Peninsula which provided the sand which was in turn transported to the Spit by wave generated longshore currents.

Knowing the estimated age of each stage, it is also possible to estimate sediment fluxes for different parts of the Spit. First, linear regression lines were fit to different segments of the gross

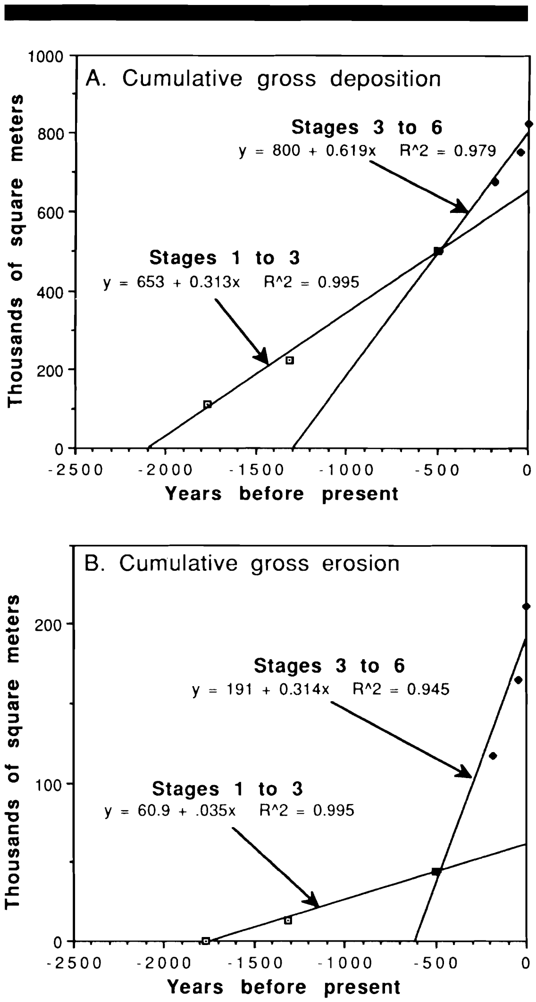

Figure 12. (A) Plot of segments of the linear regression lines for time versus cumulative areas of gross deposition, and (B) plot of segments of the linear regression lines for time versus cumulative areas of gross erosion on Penouille Spit.

deposition and gross erosion curves to calculate how the rates of areal deposition and erosion changed through time (Figure 12).

During the first 3 stages, deposition took place at the west end of the spit and erosion was concentrated at the northeast corner where the spit was attached to the coast (Figure 6A–C). For Stages 1 through 3, the slope of the regression line for gross deposition is 0.313 which gives an areal deposition rate of 313 ± 50 m^2/yr (Figure 12A). Therefore, for Stages 1 through 3, the gross sediment flux would be about 1095 ± 175 m^3/yr. For gross erosion during Stages 1 through 3, the slope of the regression line is 0.035 giving an areal erosion rate of 35 ± 6 m^2/yr and an erosional sediment flux of 120 ± 20 m^3/yr (Figure 12B). Therefore, during the first 3 stages, the average net sediment flux was 975 ± 160 m^3/yr.

During Stages 4 to 6, erosion started on the west shore and continued at the northeast corner. The slope of the regression line for gross deposition is 0.619 giving a depositional rate of 619 ± 100 m^2/yr and a gross sediment flux of 2170 ± 350 m^3/yr (Figure 12A). The slope of the erosion curve for Stages 4 to 6 is 0.314 giving an erosion rate of 314 ± 50 m^2/yr and an erosional sediment flux of 1100 ± 180 m^3/yr (Figure 12B). Therefore, the net sediment flux for Stages 4 to 6 was 1070 ± 170 m^3/yr.

At Stage 4, the net sediment flux increased from about 975 to 1070 m^3/yr while the gross sediment flux increased from about 1095 to about 2170 m^3/yr, an increase of about 1075 m^3/yr. During the same time interval, the erosional flux increased from about 120 to 1100 m^3/yr, an increase of 980 m^3/yr. The increase in gross sediment flux (1075 m^3/yr) for Stages 4 to 6 is roughly comparable to the increase in erosional flux (980 m^3/yr) over the same time interval. Therefore, during Stages 4 through 6, almost half of the sediment deposited annually along South Beach (980 ± 160 m^3/yr) eroded from West Beach, and the other half (1190 ± 190 m^3/yr) was new sediment supplied by long shore currents at the east end of the Spit.

DISCUSSION

Although the 6-stage model provides a sediment budget of erosion and deposition for Penouille Spit and can be used to estimate the age and sediment flux of the Spit, it does not tell us anything about the geologic processes that were responsible for the location and evolution of the Spit. Several conflicting hypotheses which can be put forth to account for the location and evolution of Penouille Spit include the following: (1) the location of the Spit was controlled by glacial moraines produced by valley glaciers in what is now Gaspé Bay; (2) the location of the Spit was determined by submerged river delta deposits from the l'Eau and Ascah Rivers; (3) the initiation of spit growth was controlled by changes in the rate of eustatic sea level rise and local uplift due to isostatic rebound following the retreat of the glaciers; and (4) the location of Penouille Spit midway along the north shore of Gaspé Bay was controlled by wave refraction and long shore currents in Gaspé Bay.

Glacial Origin Hypothesis

The positions of Penouille Spit and Sandy Beach about two thirds of the way inland from the mouth of Gaspé Bay could be used as evidence for a glacial origin of the Spit (Figure 2). Glacial striations and till deposits along the shore of Gaspé Bay indicate that a valley glacier extended eastward into Gaspé Bay during the waning phases of the Wisconsin glaciation (BALCO, 1992). With a waning glacier, Penouille Spit and Sandy Beach could have been formed on top of a submerged glacial moraine or from reworked morainal deposits in Gaspé Bay.

In Dingle Bay, County Kerry, Ireland, the three mid-bay bars found in the inner one-third of the bay resemble in some respects the pair of spits in Gaspé Bay (GUILCHER and KING, 1961). The two outer mid-bay bars at Dingle Bay, Rossbehy and Inch, appear to be spits formed as a result of constructive wave action. There is a gradation of grain size from the proximal to the distal ends of both spits, and the proximal end of the Rossbehy Spit appears to have been breached several times during its growth. However, the innermost mid-bay bar at Cromane Spit is composed of glacial till and is clearly of morainic origin. During the later part of the last glaciation, an ice front extended into the upper part of Dingle Bay forming moraine deposits on shore. The shingle beach along the seaward edge of the Spit is cut directly into till consisting of poorly sorted pebbles, sand, silt and clay. The moraine which is clearly visible along the length of the Spit continues onto the mainland shore adjacent to the bay.

Penouille and Sandy Beach more closely resemble Rossbehy and Inch Spits which were the result of constructive wave action, than Cromane Spit which was formed on top of an old moraine (GUILCHER and KING, 1961). The lack of morainal deposits associated with the spits on Gaspé would argue against the glacial origin of the spits. During the summer of 1991, a shallow seismic line was run along the west shore of Penouille Spit (JENCKA, 1992). The seismic velocities of the 20-meter thick sediment platform beneath Penouille corresponded to water saturated sand and silt ($\approx$1600 m/s), and were well below the velocities that could be expected for glacial till ($\approx$2600 m/s). Therefore, the absence of glacial sediments on the Spits and the low seismic velocities of sediment beneath the Spit would rule against the morainal origin of Penouille Spit.

Submerged Delta Hypothesis

The river delta hypothesis for the formation of Penouille Spit gains considerable support from the location of the Ascah and l'Eau Rivers (FISHER, 1955). The joint discharge from the two rivers could account for the submerged deltaic platform along the north shore of Gaspé Bay (Figure 2). The Ascah River has a much larger drainage basin than the l'Eau River and would have been the major contributor to the semicircular platform upon which the Spit rests.

The l'Eau River occurs near the east end of the Spit and could be considered a source of recent sediments to the Spit. The initial location of the base of the Spit coincides closely with the mouth of the l'Eau River (Figure 6A). Therefore, the submerged delta platform could have been at least partly responsible for the location of Penouille Spit and the present rivers an initial source of its sand. However, it is difficult to conclude that the rivers are solely responsible for the Spit because there is no matching river present on the south side of Gaspé Bay to account for the corresponding location of the spit at Sandy Beach.

Sea-Level Rise Hypothesis

It is possible that a change in the rate of sea-level rise could be responsible for the initiation of spit building and for the change in depositional style from deposition to erosion at the western end of Penouille Spit. Based on C^{14} ages, there was a rapid rise in sea level along the Atlantic shore of Nova Scotia (81 cm/100 yr) between 4247 and 3819 yBP and a much reduced rate of rise (27 cm/100 yr) from 3819 yBP to the present (SCOTT and MEDIOLI, 1980; BROWN and SCOTT, 1993). Sea level highs were recorded in the thick sections of peat in high marshes along the coast of Maine (GEHRELS, 1993). Radioactive C^{14} dates of 2,770 $\pm$ 65 yBP and 2,675 $\pm$ 70 yBP were recorded from salt marshes at Phillipsburg, Maine, 2,380 $\pm$ 80 yBP from the marshes at Machiasport and 2,495 $\pm$ 60 from marshes at Wells, Maine to give an average of 2580 $\pm$ 70 yBP for the coast of Maine. The average sea-level high recorded in Maine (2580 $\pm$ 70) would be about 400 years earlier than the date of 2110 $\pm$ 340 yBP estimated for the 6-stage model for the initiation of Penouille Spit (Figure 12).

Along both the north and south shores of the

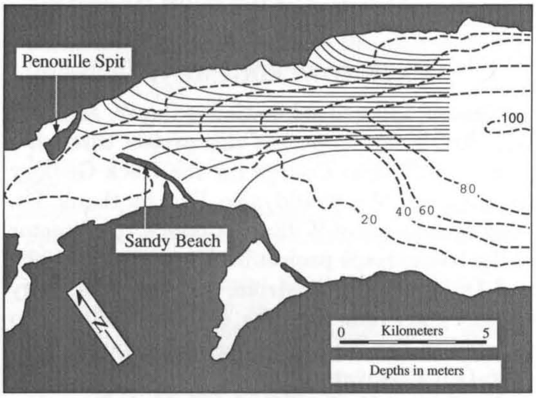

Figure 13. Wave refraction diagram for Gaspé Bay with wave rays normal to wave crests for 7 second waves approaching Penouille Spit and Sandy Beach from the Gulf of Saint Lawrence.

Saint Lawrence Estuary, the Mitis Terrace, a low accretion terrace a few hundred meters wide and about 2 meters above present sea level was built between 2,800 and 1,500 yBP with a median age of 2030 ± 50 yBP (DIONNE, 1993). This terrace located about 200 kilometers northwest of the study site on Gaspé Bay provides evidence of a local sea-level high stand around 2000 yBP.

The higher sea-level stages recorded in the marshes along the eastern Maine coast and in the terraces along the shores of the Saint Lawrence Estuary occur at about the same time as the initial formation of Penouille Spit. Therefore, there may be a causal linkage between the high sea-level stand in the Gulf of Saint Lawrence and the wave refraction pattern in the bay which resulted in the initial development of Penouille Spit.

Wave Refraction Hypothesis

According to the wave refraction hypothesis, the wave refraction pattern in Gaspé Bay determined the strength and direction of longshore currents along the north and south shores and was responsible for the location and evolution of Penouille Spit and Sandy Beach. Waves which swept into Gaspé Bay from the Gulf of Saint Lawrence were refracted along the margins of the bay. The wave refraction diagram of Gaspé Bay is a plot of wave rays for storm waves or swells with periods of 7 seconds (Figure 13). The wave rays which are normal to the wave crests diverge as they approach Penouille Spit and Sandy Beach. The wave rays along the north shore of Gaspé Bay bend to the north, and those along the south shore of the bay bend to the southwest. The wave crests normal to the wave rays break with acute angles along the shore (Figure 13). As the waves progress up the bay, westward flowing longshore currents are generated along the north coast of the bay toward Penouille Spit. As the wave rays spread midway up the bay, the angle between the wave crest and the shoreline decreases and the wave height drops. The decrease in wave angle and breaker height causes velocity of the longshore current to decrease. As the velocity of the longshore current drops, its carrying capacity also decreases and sediment is deposited along the shore forming a midbay bar (MAY and TANNER, 1973).

During the first three stages of spit development, waves breaking directly on the Spit generated longshore currents which flowed toward the southwest end of the Spit (Figure 13). The build up of sediment to the east of the groin in a 1948 aerial photograph and its subsequent redistribution in a 1970 photograph provide evidence for the westward longshore transport along the south shore of the Spit. The decrease in mean grain size from 0.5 ϕ to 01.0 ϕ along the south shore provides additional evidence of westward longshore transport (HANEY, 1990). As the Spit grew westward, erosion was concentrated at the eastern end of the Spit and new ridges were added along its southwest shore (Figures 7A and 7B).

The change in depositional pattern on Penouille Spit at the beginning of Stage 4 can be accounted for by the wave refraction pattern on Sandy Beach (Figure 13). As Penouille Spit continued to grow to the southwest, Sandy Beach also continued to grow to the north. Eventually, Penouille came under the blocking influence of Sandy Beach and waves which would previously have broken along the south half of Penouille were refracted into Sandy Beach.

At the beginning of Stage 4, longshore currents on South Beach were no longer strong enough to transport sediment all the way to the west end of the Spit. Waves from the west generated by southwest winds across the upper end of Gaspé Bay combined with ebb tidal currents to start erosion along the west end of Penouille Spit. At the beginning of Stage 4, sand eroded from West Beach was transported eastward and deposited midway along the south coast (Figure 7A). The weakened, westward longshore transport along South Beach also contributed to the bulge along the south coast. During Stages 5 and 6, erosion continued along the western shore resulting in the deposition of spits at the north and south ends of West Beach which eventually closed off a tidal marsh at the southwest tip of Penouille (Figures 7B and 7C).

Although the initial location of the Spit may have been determined by the submerged delta of the l'Eau River, the evolution and final configuration of the Spit were controlled by the wave refraction patterns, longshore transport and tidal currents.

CONCLUSIONS

A 6-stage model of origin and evolution of Penouille Spit is based on field mapping, shoreline traces on old maps, and aerial photographs of relict beach ridges. Maps and aerial photos of shorelines dating from 1765 to 1981 were used to determine the rate of beach erosion (0.50 ± 0.8m/yr) along the western shore. Forty-one beach ridges were grouped into 6 clusters which represent the 6 depositional stages of the spit. The rate of shoreline erosion was correlated with rates of areal deposition and erosion of ridge clusters to estimate the rate of ridge accretion (45.5 ± 7.3 yrs/ridge), average sediment flux (1,000 ± 160 m^3/yr) and age (2,110 ± 340 yBP) of Penouille Spit.

The location of Penouille Spit within Gaspé Bay was determined by fluvial and deltaic processes during the Holocene rise in sea level. Deposition of the present spit was initiated about 2110 ± 340 yBP close to a high sea level stand along the Maine coast (2580 ± 70 yBP) and a local high sea level stand represented by the Mitis Terrace on the south coast of the Saint Lawrence Estuary (2030 ± 50 yBP).

The subsequent growth and evolution of the Spit were controlled by waves, longshore transport and tidal patterns within Gaspé Bay. From about 2110 ± 340 to 500 ± 80 yBP, waves from the Gulf of Saint Lawrence swept into Gaspé Bay generating longshore transport which produced Penouille Spit on the north shore and Sandy Beach on the south shore of the bay. During that time, Penouille expanded westward about 2.4 km and enclosed a broad salt marsh. At about 500 ± 80 yBP, the northward expansion of Sandy Beach partially blocked the waves from the Gulf of Saint Lawrence resulting in erosion along the west shore of Penouille. At 180 ± 30 yBP, the westward flowing longshore current and ebb tidal current converged to produce a pair of recurved spits at the southwest corner of the Penouille. At 45 ± 7 yBP, the corner spits merged to enclose a salt marsh at the southwest tip of the Spit resulting in the present configuration of Penouille.

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